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REVIEW ARTICLE

# Agroforestry - An elixir for soil health management and carbon sequestration

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## Abstract

Intensive agricultural practices have resulted in in significant soil degradation, nutrient imbalances and the decline of vital ecosystem services, thereby necessitating the adoption of i sustainable land-use strategies. Agroforestry, an integrated land management system that combined with crops and livestock, played a key role in restoring soil health and increasing carbon sequestration. This review discussed the mechanisms through which agroforestry improved soil nutrient cycling, enhanced the accumulation of organic matter and strengthened soil structure, thereby reducing erosion and improving water retention. The roles of tree litter decomposition, deep-rooted species and microbial interactions in increasing soil fertility and biodiversity were also highlighted. Furthermore, the review examined agroforestry's potential for carbon sequestration, with estimates indicating that such systems could sequester 0.29 to 15.2 Mg C ha$^{-1}$ year$^{-1}$. Above Ground Biomass (AGB) accumulation and Below Ground Biomass, (BGB) root inputs contributed significantly to long-term soil carbon stabilization. Agroforestry also aided in greenhouse gas mitigation by enhancing nitrogen use efficiency, facilitating methane oxidation and regulating $CO_2$ flux. Various agroforestry models, including silvopastoral systems, alley cropping were explored for their applications in both degraded and saline soils. Additionally, the review addressed challenges such aseconomic and policy barriers, the need for secure land tenure and advancements in carbon monitoring technologies. This findings underscored the necessity for stronger policy support, financial incentives and large-scale adoption of agroforestry to enhance soil health, mitigate climate change and promote sustainable agriculture.

**Keywords:** above ground biomass; below ground biomass; climate change mitigation; ecosystem services; soil erosion

## Introduction

Soil degradation was a critical global issue, that negatively impacted agricultural productivity, environmental sustainability and climate resilience (1). In India around 147 million hectares (Mha) were degraded with major cause including water erosion (94 Mha), acidification (16 Mha), flooding (14 Mha), wind erosion (9 Mha), salinity (6 Mha) and multiple factors (7 Mha) (2). Globally, 33 % of land was affected, leading to a 60 % decline in soil ecosystem services between 1950 and 2010 (3). The loss of Soil Organic Matter (SOM) owing to intensive farming, deforestation and climate change intensified issues like soil erosion, desertification and nutrient depletion. As global temperature rose and food demand increases, sustainable soil management became essential for restoring fertility, and mitigating climate change (4).

Agroforestry, an integrated land-use system that combined trees with crops and/or livestock, emerged as a nature-based solution to mitigate soil degradation while enhancing carbon sequestration (5). By incorporating deep-rooted trees and diverse plant species, agroforestry promoted the accumulatio of SOM , improved nutrient cycling and reduced soil erosion, thereby increasing overall soil resilience (6). One of the most substantial contributions of agroforestry was its ability to sequester atmospheric carbon both aboveground and belowground, thereby reducing greenhouse gas (GHG) emissions. Studies showed that AGB in agroforestry systems stored between 12 to 228 Mg C ha$^{-1}$, depending on tree species, management practices and climatic conditions. Belowground carbon sequestration, primarily through root biomass and soil organic carbon (SOC) storage, was estimated to range from 2.8 to 48.7 Mg C ha$^{-1}$ across different agroforestry systems.

The importance of soil carbon sequestration lay in its role as a climate mitigation strategy, helping to offset carbon emissions while enhancing soil fertility. SOC, which comprises about 58 % of SOM, played a fundamental role in nutrient cycling, soil structure stabilization and water retention. However, land-use changes and intensive cropping have led to severe SOC depletion, making it necessary to adopt practices that enhanced carbon sequestration potential. Research suggested that agroforestry-based soil management strategies, such as silvopastoral systems, alley cropping and multistrata agroforestry, had the potential to increase SOC stocks by 10-40 % compared to conventional agriculture (7). Additionally, the Intergovernmental Panel on Climate Change (8) recognized agroforestry as a key strategy for carbon sequestration, with the capacity to sequester up to 1.1-3.04 Pg C $yr^{-1}$ globally (9).

Maintaining soil health was central to sustainable agriculture, as it influenced crop productivity, water retention and long-term food security. Agroforestry not only contributed to soil carbon sequestration but also enhanced soil microbial diversity, promoted nutrient cycling and improved erosion control through root stabilization and organic matter inputs (10). Given its multifunctional role, this review aimed to examine agroforestry's potential for soil health management and carbon sequestration, focusing on the mechanisms that drove carbon storage in agroforestry systems. It further explored the impact of agroforestry on soil microbial activity, nutrient cycling and erosion control, while evaluating the economic and ecological benefits of different agroforestry models. Additionally, this review highlighted the challenges and opportunities associated with the adoption of agroforestry for soil restoration and climate change mitigation. By addressing these aspects, this review underscored the transformative potential of agroforestry in enhancing soil ecosystem services, augmenting carbon sequestration and contributing to global climate resilience.

## Role of agroforestry in soil health management

Agroforestry was a sustainable land management system that integrated trees, crops and livestock on the same land to boost biodiversity, recover soil health and intensified farm productivity (Fig. 1). Combined agricultural and forestry practices creates a more resilient ecosystem advancing both the environment and rural livelihoods. By promoting soil conservation, carbon sequestration and climate adaptation, agroforestry played a crucial role in sustainable agriculture and natural resource management (11, 12). This approach not only supported food security but also contributed to ecological balance, making it a key strategy in addressing global environmental challenges.

## Agroforestry and nutrient management

Agroforestry played a critical role in enhancing soil fertility and nutrient cycling through mechanisms such as biological nitrogen fixation, organic matter addition and nutrient retention. Integrating leguminous trees within cropping systems naturally enriched the soil with nitrogen, reducing dependency on synthetic fertilizers. Species like *Faidherbia albida*, *Sesbania sesban* and *Gliricidia sepium* established symbiotic relationships with rhizobial bacteria, enabling them to convert atmospheric nitrogen ($N_2$) into plant-available ammonium ($NH_4^+$). Research indicated that nitrogen-fixing agroforestry systems could contribute 50 to 800 kg N $ha^{-1}$ $yr^{-1}$, depending on species, soil conditions and management practices (13). Additionally, the continuous leaf litter and root turnover in these systems enhanced SOM accumulation, microbial activity and overall soil structure.

Nutrient retention was another key benefit of agroforestry, as deep-rooted trees accessed subsoil nutrients and recycled them to the topsoil through litter decomposition and root exudates. Studies showed that systems incorporating *Grevillea robusta* and *Acacia mangium* reduced nitrate leaching losses by 30–50 %, improving nutrient-use efficiency (14). Moreover, agroforestry systems mitigated soil erosion by 40–80 % compared to monoculture farming, safeguarding essential topsoil nutrients. By integrating these principles with Integrated Nutrient Management (INM), which combined organic and inorganic inputs, agroforestry optimized nutrient accessibility and crop yield. For example, wheat cultivated under *Grewia optiva* with 50 % Recommended Dose of Fertilizers (RDF) and 50 % Farm Yard Manure (FYM) significantly improved yield (15). Similarly, lentil intercropped with *Grewia optiva* under 100 % FYM application confirmed superior soil properties and productivity (16).

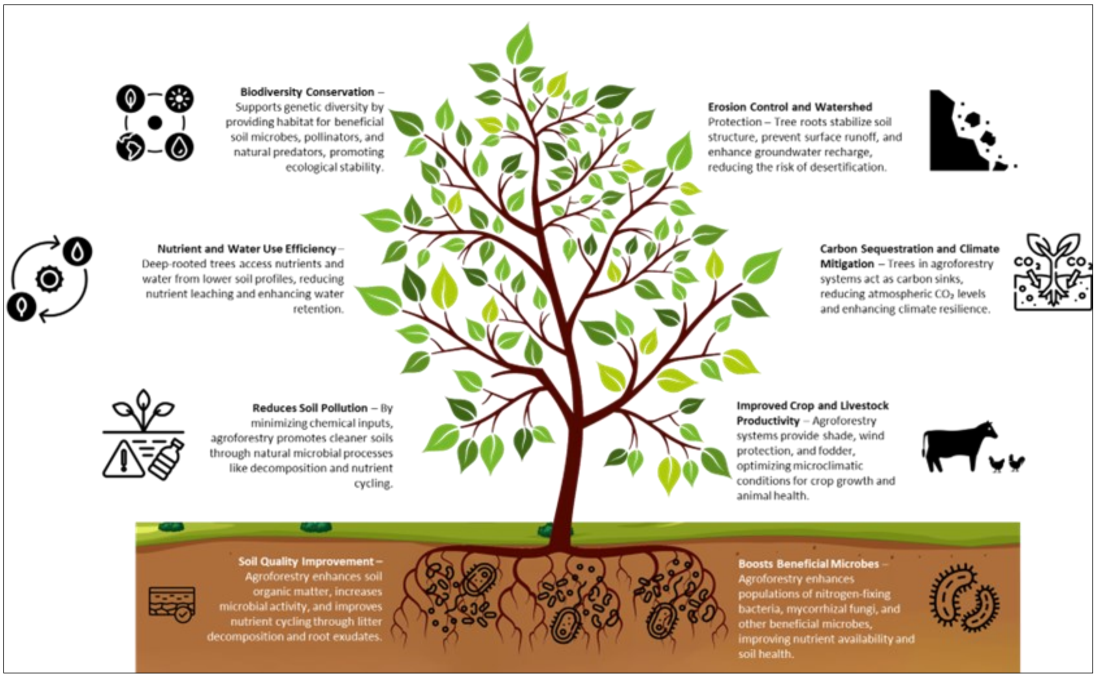


**Fig. 1.** Impact of agroforestry on soil quality enhancement and microbial dynamics.

## Soil biodiversity and microbial activity in agroforestry systems

Agroforestry systems significantly enhanced soil biodiversity and microbial activity by promoting a diverse and functionally rich soil microbiome. The integration of trees, crops and livestock created a complex below-ground ecosystem where microbial communities thrived due to increased organic matter inputs, diverse root exudates and stable microhabitats. Studies indicated that agroforestry systems outperformed monoculture in terms of microbial diversity and biomass, leading to improved soil health and sustainable agricultural productivity (17). The heterogeneous vegetation structure in agroforestry fostered microbial diversity, increasing microbial biomass carbon and nitrogen in soils (18). Similarly, agroforestry soils showed higher levels of arbuscular mycorrhizae fungi, beneficial bacteria and enzyme activities, which were attributed to improved SOC and microclimate conditions (19).

Agroforestry practices enhanced nutrient cycling, leading to greater nitrogen mineralization and higher stocks of essential nutrients such as nitrogen, phosphorus as well as potassium in soil and litter (20). In cocoa agroforestry systems, metagenomic studies revealed increased populations of *Proteobacteria* and *Basidiomycota*, which played critical roles in carbon and nitrogen cycling (17). A key component of agroforestry soil microbiomes was arbuscular mycorrhizal (AM) fungi, which formed symbiotic associations with plant roots, increasing phosphorus uptake efficiency by 35-70 % compared to conventional agriculture (6). AM fungi also contributed to soil aggregation through the production of glomalin, a glycoprotein that enhanced soil structure and water retention, with concentrations found to be 40 % higher in agroforestry plots with leguminous trees (21).

Beyond nutrient cycling, soil biodiversity in agroforestry played a crucial role in disease suppression and carbon sequestration. A diverse microbial community suppressed soil-borne pathogens by competing for resources and producing antimicrobial compounds, reducing the frequency of diseases such as root rot and wilt. Additionally, microbial biomass contributed to carbon sequestration, with agroforestry systems storing 0.5-2.5 Mg C $ha^{-1}$ $yr^{-1}$ in the soil, compared to lower carbon storage rates in monoculture farming (22). In maize-banana agroforestry systems in Kenya, microbial diversity and biomass were significantly higher in treatments integrating trees, leading to heightened soil enzyme activity and nutrient availability (23). However, microbial activity varied with seasonal changes and different agroforestry system designs (24).

While agroforestry provided numerous benefits for soil biodiversity and microbial activity, challenges such as land management practices and anthropogenic impacts still threatened these ecosystems. Sustaining a balance between agricultural productivity and biodiversity conservation was crucial. Future research needed to focus on optimizing agroforestry practices to maximize microbial benefits, progress soil fertility and augment long-term agricultural sustainability (19).

## Soil erosion control and water retention in agroforestry systems

Agroforestry systems played a crucial role in mitigating soil erosion and enhancing water retention by integrating trees, shrubs and crops into farming landscapes. Soil erosion was a major challenge in conventional agricultural systems, leading to the loss of topsoil, reduced fertility and diminished water-holding capacity (1). The strategic placement of trees and shrubs in agroforestry systems acted as a natural barrier against both wind and water erosion, thereby preserving soil structure and promoting sustainable agricultural productivity. Studies estimated that agroforestry practices had the potential to protect over 300 million hectares of farmland worldwide from erosion-related degradation.

### Soil erosion control

Agroforestry techniques were shown to significantly reduce soil erosion compared to conventional agricultural practices. Studies in Mexico, Algeria, Brazil and Minas Gerais validated that agroforestry systems substantially reduced soil and water losses (25, 26). In Mexico, an agroforestry system with *Leucaena leucocephala* and *Moringa oleifera* reduced soil loss from 16.67 to 2.17 Mg $ha^{-1}$ $year^{-1}$ (27). Similarly, in Algeria, agroforestry improved soil protection, humidity and fertility (28). Brazilian studies revealed that agroforestry systems had lower soil and nutrient losses compared to conventional methods, particularly in areas with high soil mobilization (25, 26). These findings highlighted the ecological sustainability of agroforestry systems and their ability to preserve natural resources, emphasizing the need for conversion from conventional to more sustainable agricultural practices.

Research indicated that agroforestry practices could reduce soil erosion by up to 97 %. In semiarid Kenya, mulch cover from *Senna siamea* reduced soil loss to only 13 % of the average loss (29). Additionally, techniques such as contour cultivation and hedgerow intercropping have demonstrated significant reductions in soil erosion, with reductions of up to 48 % in soil loss compared to conventional practices (30, 31)

One of the most effective agroforestry strategies for erosion control was the establishment of windbreaks and shelterbelts, which consisted of rows of trees planted along field edges to reduce wind velocity. Wind erosion was particularly severe in dryland agriculture, where strong winds remove fine soil particles, leading to the degradation of soil organic matter and nutrient depletion. Research indicated that properly designed windbreaks could reduce wind speed by 30-50 %, thereby minimizing soil loss by up to 85 % in arid and semi-arid regions (22). Besides, shelterbelts effected micro-climatic conditions by reducing evapo-transpiration and promoted moisture retention in the soil. This mechanism not only prevented soil degradation but also improved water availability for crops, contributing to increased yields in wind-prone agricultural landscapes.

### Water retention

Agroforestry significantly enhanced soil water-holding capacity through improved infiltration and reduced surface runoff. Tree roots created macropores in the soil, facilitating deeper water penetration and reducing the risk of water loss due to surface runoff (32). Studies illustrated that agroforestry augmented soil structure and increases water retention capacity, which was vital for preserving soil moisture during dry periods (26).

Agroforestry systems were found to increase soil porosity and infiltration rates by 20-45 %, leading to greater water retention in the root zone (33). A differential analysis between agroforestry and conventional wheat monocultures revealed that agroforestry systems retained 411 mm $ha^{-1}$ of water, whereas monocultures retained only 283 mm $ha^{-1}$, demonstrating a significant enhancement in soil moisture conservation (34). Moreover, tree litter and organic matter in agroforestry systems develop water retention by increasing SOC, which improves soil aggregation and its capacity to retain water.

The existence of trees in agroforestry systems also created a favorable microclimate that reduced evaporation and enhanced water conservation, leading to better crop yields (35). Beyond crop fields, agroforestry contributed to hillside stabilization and watershed protection, mainly in sloping landscapes prone to severe soil erosion. The deep and extensive root systems of agroforestry tree species, such as *Leucaena leucocephala* and *Gliricidia sepium*, aided in anchoring the soil and reduce the risk of landslides and runoff -induced erosion. Terracing combined with agroforestry practices was exposed to decrease soil loss rates by 50-70 %, significantly strengthening long-term soil sustainability (36).

Moreover, agroforestry buffers around rivers and lakes played a vital role in sieving sediments and nutrients from runoff, thereby shielding water quality and upholding watershed health (37). While agroforestry systems delivered substantial benefits for soil and water conservation and their acceptance remains limited due to various socio-economic barriers. Addressing these challenges was indispensable for maximizing the potential of agroforestry in sustainable agriculture.

## Contribution of agroforestry to ecosystem services

Agroforestry systems significantly enhanced ecosystem facilities by endorsing biodiversity, refining soil and water quality and increasing carbon sequestration, making them a sustainable land-use strategy. The integration of trees, crops and livestock in agroforestry system fostered diverse habitats that supported pollinators and natural pest predators, resulting in a 30-50 % increase in pollinator abundance and a 25-40 % reduction in pest outbreaks(19, 38, 39). Additionally, agroforestry improved soil hydrology by increasing infiltration rates by 25-50 %, reducing sediment runoff by 60-90 % and enhancing groundwater recharge by 15-30 % (40). These systems mitigated soil erosion by up to 80 % through windbreaks and shelterbelts, thereby stabilizing degraded landscapes (41). Carbon sequestration in agroforestry systems ranged from 0.29 to 15.2 Mg C $ha^{-1}$ $year^{-1}$, with SOC stocks increasing by 20-60 % over two decades, significantly improved soil fertility (42). Agroforestry landscapes also reduced nitrate leaching and enhance nutrient cycling, leading to a 21 % increase in SOC and improved nitrogen and phosphorus availability (43). Though agroforestry stores less carbon than natural forests, it sequesters more than monoculture systems, thereby contributing to climate change through the reduction $CO_2$ emissions associated with land degradation (44). Moreover, these systems provided critical resources such as food, fuelwood and fodder, thereby strengthening economic resilience and food security, particularly in climate-vulnerable regions (44). Despite variations in effectiveness due to environmental conditions and management practices, agroforestry remained vital nature-based solution for enhancing biodiversity, restoring degraded ecosystems and supporting sustainable agriculture.

## Agroforestry and carbon sequestration: a strategy for climate change mitigation

Agroforestry played a key role in mitigating climate change by enhancing carbon sequestration, reducing greenhouse gas emissions and improving resilience to climate variability (Fig. 2). As a sustainable land-use strategy, agroforestry integrated trees with agricultural systems, enabling the capture and storage of atmospheric carbon while simultaneously refining soil health and ecosystem stability (45). Through carbon sequestration in both biomass and soil, along with reduced emissions from agricultural inputs, agroforestry provides a feasible solution for reducing agriculture's carbon footprint (46).

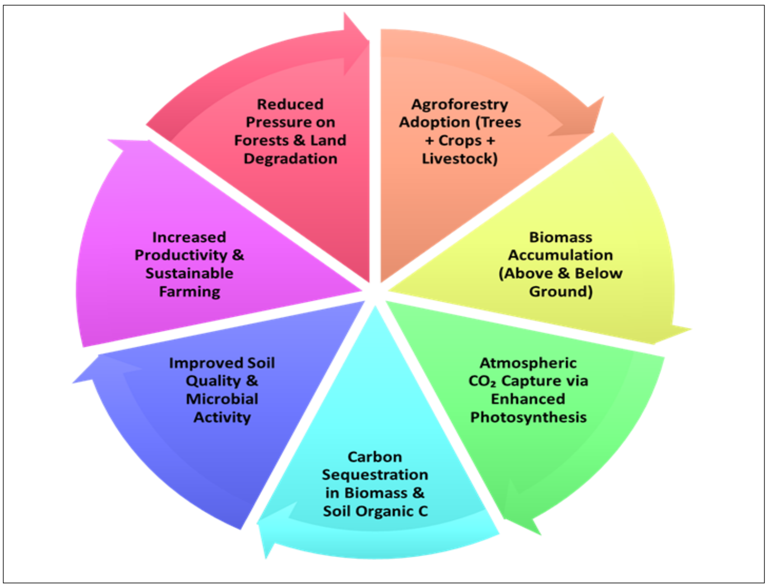


**Fig. 2**. Multifunctional benefits of agroforestry systems for enhancing climate resilience and promoting sustainable agriculture.

Soil served as a major carbon reservoir, storing approximately 950 Gt of soil inorganic carbon and 1,550 Gt of SOC (47). Agroforestry played a crucial role in soil carbon sequestration by enhancing organic matter accumulation, improving nutrient status and mitigating climate change. Using the $CO_2$ FIX simulation model, the net carbon sequestered over a period of 30-year in agroforestry systems across 51 districts in 16 states was assessed (Fig. 3, Table 1). The results indicate that net carbon sequestration exceeded 11.35 t C $ha^{-1}$ from the baseline, with higher sequestration in states like Himachal Pradesh, Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh, Telangana, and Odisha (>10.0 t C $ha^{-1}$) (48). In contrast, Gujarat, West Bengal, Haryana, and Chhattisgarh exhibited lower sequestration rates (<5 t C $ha^{-1}$), while Madhya Pradesh, Punjab, Rajasthan, Bihar, and Uttar Pradesh fell within the 5-10 t C $ha^{-1}$ range (49).

The carbon sequestration potential (CSP) across different states (Fig. 4, Table 1) highlighted Maharashtra as the leading state, followed by Himachal Pradesh and Tamil Nadu. Andhra Pradesh recorded the highest baseline carbon stock (35.13 t C $ha^{-1}$), trailed by Himachal Pradesh and Odisha. On average, the CSP of agroforestry systems in these states was 0.35 t C $ha^{-1}$, with total CSP ranging from 0.032 to 1.849 million tonnes of carbon. The overall carbon sequestration potential of agroforestry systems across the 16 states (Table 2) was estimated at 7.23 million tonnes of carbon (50).

## Aboveground carbon sequestration in agroforestry

Agroforestry systems played a critical role in aboveground carbon sequestration, contributing significantly to climate change mitigation by enhancing carbon storage in biomass. Trees in agroforestry systems performance as carbon sinks, capturing atmospheric $CO_2$ through photosynthesis and storing it in different parts of plant. Studies indicated that aboveground biomass carbon (ABGC) in agroforestry systems ranges from 267.05 Mg C/ha to 324.70 Mg C/ha in Thailand (51), where as in India, it is reported approximately 2233 g of carbon over 50 years (52). Species selection was important, with combinations such as *Morinda tinctoria* and *Emblica officinalis* representing higher carbon sequestration rates, reaching 1331 kg C/ha (53). Globally the carbon sequestration potential of agroforestry was estimated at up to 2.2 Pg C over 50 years, with SOC storage reaching up to 300 Mg C/ha at a 1 m depth (54). Compared to conventional croplands storing 30-50 Mg C/ha, agroforestry systems stored between 50-150 Mg C/ha, indicating their superior long-term carbon sequestration capacity (31). Furthermore, technological advancements such as geospatial analysis and machine learning have amended the accuracy of biomass estimation, achieving $R^2$ values up to 0.69 (55). Windbreaks, a form of agroforestry, exhibited carbon sequestration rates comparable to forests, emphasizing their

**Table 1.** Total carbon stock, net carbon sequestered and carbon sequestration potential across different states (50).

| State | Tree density (Tree/ha) | Total carbon stock in baseline (t C $ha^{-1}$) | Net carbon sequestered over simulated period of 30 years (tT C $ha^{-1}$) | CSP (t C $ha^{-1}Yr^{-1}$) |
|---|---|---|---|---|
| Uttar Pradesh | 11.75 | 15.15 | 7.19 | 0.25 |
| Gujarat | 4.02 | 20.26 | 3.29 | 0.11 |
| Bihar | 9.82 | 15.28 | 7.51 | 0.22 |
| West Bengal | 5.45 | 14.35 | 3.68 | 0.12 |
| Rajasthan | 9.70 | 22.29 | 7.05 | 0.49 |
| Punjab | 17.90 | 17.32 | 7.71 | 0.25 |
| Haryana | 4.37 | 15.19 | 2.69 | 0.09 |
| Himachal Pradesh | 36.69 | 33.48 | 28.36 | 0.65 |
| Maharashtra | 41.80 | 27.70 | 28.95 | 0.82 |
| Madhya Pradesh | 9.73 | 21.24 | 5.54 | 0.18 |
| Karnataka | 27.57 | 28.36 | 10.55 | 0.35 |
| Tamil Nadu | 25.74 | 24.50 | 17.95 | 0.60 |
| Andhra Pradesh | 23.09 | 35.13 | 15.55 | 0.51 |
| Telangana | 7.92 | 21.76 | 13.93 | 0.46 |
| Odisha | 55.93 | 32.58 | 18.61 | 0.49 |
| Chhattisgarh | 3.27 | 16.59 | 3.07 | 0.19 |
| **Mean** | **18.42** | **22.97** | **11.35** | **0.35** |

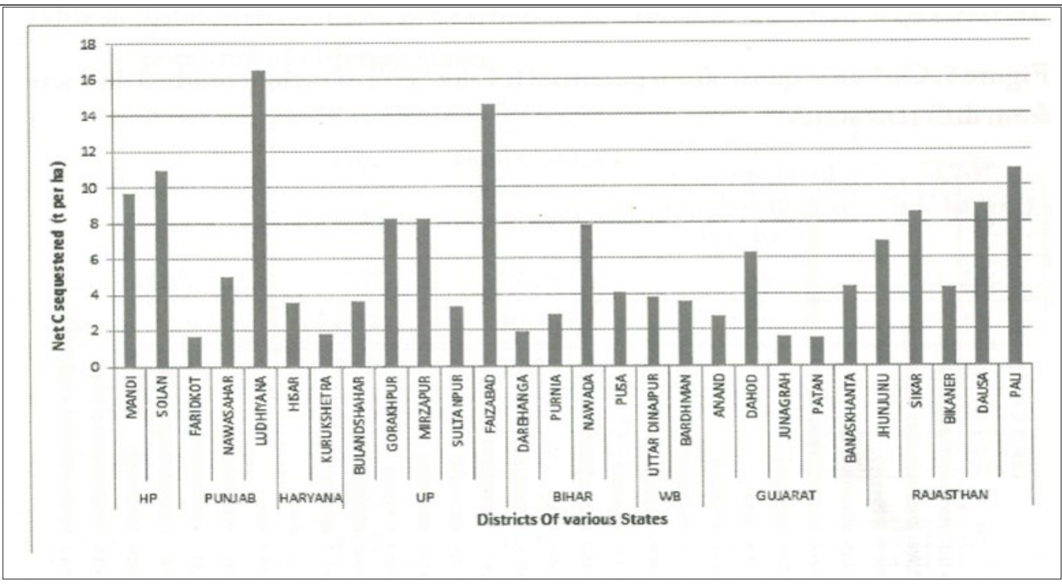


**Fig. 3.** Net carbon sequestered (t $ha^{-1}$) by existing agroforestry system across different states (50).

**Table 2**. Agroforestry area, tree density and carbon sequestration potential (CSP) across different states (50).

| State | Agroforestry area (Mha) | Annual CSP (t C ha$^{-1}$Yr$^{-1}$) | Total CSP (million t C) |
|---|---|---|---|
| Uttar Pradesh | 1.971 | 0.25 | 0.472 |
| Gujarat | 1.089 | 0.11 | 0.119 |
| Bihar | 0.795 | 0.22 | 0.199 |
| West Bengal | 0.405 | 0.12 | 0.050 |
| Rajasthan | 2.051 | 0.49 | 0.482 |
| Punjab | 0.420 | 0.25 | 0.108 |
| Haryana | 0.352 | 0.09 | 0.032 |
| Himachal Pradesh | 0.327 | 0.65 | 0.309 |
| Maharashtra | 1.916 | 0.82 | 1.849 |
| Madhya Pradesh | 1.346 | 0.18 | 0.248 |
| Karnataka | 1.293 | 0.35 | 0.455 |
| Tamil Nadu | 0.688 | 0.60 | 0.412 |
| Andra Pradesh | 1.673 | 0.55 | 0.853 |
| Telangana | 0.804 | 0.49 | 0.499 |
| Odisha & Chhattisgarh | 0.601 | 0.19 | 1.140 |
| **Mean** | **15.73** | **0.35** | **7.230** |

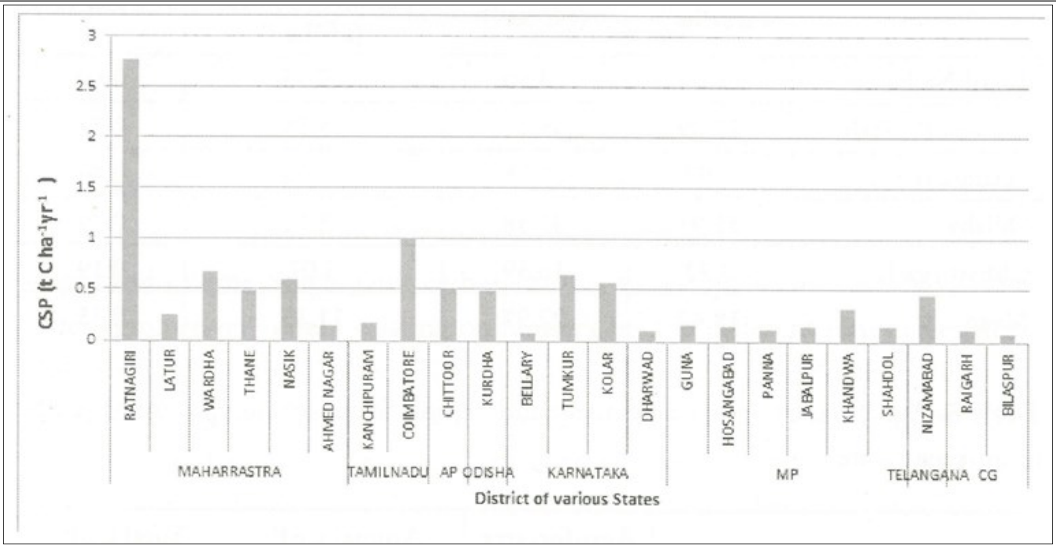


**Fig. 4.** Carbon sequestration potential (t C ha$^{-1}$ yr$^{-1}$) of various studied districts across different states (50).

role in sustainable land use (56). Despite challenges in accurately estimating carbon storage due to site-specific factors (57), agroforestry remained a feasible compromise between reforestation and agricultural production, contributing a nature-based solution to carbon sequestration and climate change mitigation.

## Biomass accumulation in agroforestry trees

Biomass accumulation in agroforestry trees was a key factor in carbon sequestration. Fast-growing tree species namely *Acacia nilotica*, *Gliricidia sepium* and *Leucaena leucocephala* exhibited high photosynthetic proficiency and rapid growth, leading to greater carbon fixation (58).

Agroforestry systems demonstrated significant potential for biomass accumulation and carbon sequestration. Experimentations illustrated that tree species diversity, age and regional climate influence carbon accumulation in these systems (59). Fast-growing species including *Acrocarpus fraxinifolius* and *Eucalyptus tereticornis* exhibited high biomass accumulation and carbon storage potential. And stem biomass generally contributed the most to carbon storage, although roots and litter also played critical roles in soil carbon sequestration (60). Agroforestry systems with numerous tree species accumulated biomass carbon faster than single-species systems (59). Under irrigated conditions, species among them *Albizia procera* showed high biomass productivity and carbon storage (61). Regional climate affected soil carbon dynamics, with tropical zones displaying rapid increases and temperate zones exhibiting slower but eventually higher soil carbon levels (59). These findings highlighted the importance of agroforestry in mitigating climate change through enhanced carbon sequestration.

Agroforestry systems could sequester 4-12 Mg C ha$^{-1}$ yr$^{-1}$ (33), while agroforestry trees reported to accumulate 50 - 100 Mg C ha$^{-1}$ over a 20-30-year period (31). Reports related to alley cropping system with *Grevillea robusta* stored 70 Mg C ha$^{-1}$ in biomass after 25 years, significantly higher than monoculture maize systems (10 Mg C ha$^{-1}$) (22). This highlighted the superior carbon sequestration potential of agroforestry related to conventional agricultural systems.

## Carbon storage potential of different agroforestry species

The carbon storage potential of agroforestry species varied related to their growth rate, wood density and lifespan. High-carbon sequestration species including *Tectona grandis* (Teak) and *Dalbergia sissoo* (Indian Rosewood) could store 80 -150 Mg C ha$^{-1}$ over a 30-year period. Nitrogen-fixing trees like *Acacia senegal* and *Prosopis juliflora* enhanced soil fertility and also contributed to long-term carbon storage. Different agroforestry systems also exhibited varying carbon sequestration rates. Carbon sequestration rate of home gardens (8 -12 Mg C ha$^{-1}$ yr$^{-1}$), silvopastoral systems (20 -30 Mg C ha$^{-1}$) over 15 years and windbreaks/shelterbelts (10-25 Mg C ha$^{-1}$), reducing carbon loss from soil degradation (57). In agroforestry systems various tree species displayed different capacities for carbon fixation. *Populus deltoides*, *Eucalyptus tereticornis* and *Acrocarpus fraxinifolius* exhibited high AGB accumulation (60). *Leucaena leucocephala* exhibited the highest potential among species studied in Bangladesh (62). Reports show that *Bombax ceiba* and *Bauhinia variegata* established high capacity (63). Structural composition, number of woody perennials and management practices influenced biomass levels and carbon storage in agroforestry systems (64). Compared to boundary plantation, block plantations of *Populus deltoides* with wheat or lemon grass exhibited high potential (64). Particularly, stem biomass was the largest carbon store, but litter and roots also played crucial roles in soil carbon absorption (60). Overall, agroforestry systems could capture more carbon than sole agricultural land use systems (64).

## Comparative carbon sequestration rates: agroforestry vs. monocultures

Agroforestry systems (AFS) exhibited significantly higher and more sustained rates of carbon storage than monocultures, making them a vital strategy for mitigating climate change. Annual cropping and agroforestry systems store 0.5 -3 Mg C ha$^{-1}$ yr$^{-1}$ and 6 -12 Mg C ha$^{-1}$ yr$^{-1}$ respectively, depending on species selection and management practices (65). Report from Sub-Saharan Africa showed that maize monocultures stored 2.3 Mg C ha$^{-1}$ yr$^{-1}$, whereas maize intercropped with *Faidherbia albida* much higher rate of 6.8 Mg C ha$^{-1}$ yr$^{-1}$.This signified the ability of AFS to enhance sequestration efficiency by nearly threefold (65). Similarly, in West Africa, an agroforestry parkland system (55 Mg C ha$^{-1}$) in AGB compared to monocultures (20 Mg C ha$^{-1}$), confirming a two- to threefold increase in carbon storage capacity (66). Across various African and South American landscapes, AFS exhibited superior carbon sequestration potential, accumulating 0.2-5.8 Mg C ha$^{-1}$ yr$^{-1}$, with rotational woodlots displaying the highest sequestration rates (67). In Bolivia, successional agroforestry systems stored 143.7 Mg C ha$^{-1}$, significantly surpassing monocultures (86.3 Mg C ha$^{-1}$) (68). This enhanced sequestration was attributed to higher tree diversity, increased litterfall and improved soil fertility in AFS (69). Furthermore, AFS contributed to long-term carbon stabilization through BGB, with deep-rooted species facilitating soil carbon storage beyond 1 meter depth (54). The economic potential of carbon fixation in AFS was another consideration, as carbon revenue could enhance their profitability and incentivize adoption among smallholders. However, at current carbon market prices, annual revenues remained modest, often below $ 30 ha$^{-1}$ yr$^{-1}$ (67), highlighting the need for policy support and financial incentives to enhance adoption. Particularly, organic certification was linked to increased tree diversity in cocoa production systems, indicating a potential pathway for transitioning from monocultures to agroforestry while improving both ecosystem services and economic viability (68). These findings reinforced that agroforestry offered a scalable, multifunctional approach to carbon sequestration, biodiversity conservation and sustainable land use, outperforming monocultures in both ecological and economic terms.

## Role of root biomass in soil organic carbon accumulation

Root biomass was a key factor influencing accumulation of SOC, with studies demonstrating a strong positive correlation between root distribution and SOC content across different soil types and ecosystems (70, 71). Approximately 50-70 % of total root biomass and SOC was concentrated in the upper 30 cm of soil, where fine roots, root exudates and microbial interactions contributed to carbon stabilization (70, 71). Root traits such as elongation rate, diameter and biochemical composition significantly influenced SOC accumulation. Hemicellulose-rich roots increased carbon storage in the coarse silt fraction, while lignin-rich roots with high C: N ratios contributed up to 60 % of particulate organic matter, enhancing long-term SOC stability (72). Cover crops were shown to increase SOC stocks by 10-30 % over a decade, with species-specific traits and diverse cover crop mixtures optimizing carbon inputs across different environmental conditions (73). In temperate regions, deep-rooted species such as alfalfa and clover contributed up to 1.5 Mg C ha$^{-1}$ yr$^{-1}$., while in tropical agroforestry systems, deep-rooted trees like *Faidherbia albida* and *Gliricidia sepium* enhance SOC stocks by 20-50 % over two decades (73). Microbial decomposition played a crucial role in carbon transformation, with microbial biomass contributing 5-15 % of total SOC and enzymatic activity influencing the stabilization of organic matter into long-lived soil carbon pools (73). Understanding the interactions between root traits, microbial activity and carbon sequestration was essential for optimizing soil management strategies to enhance SOC storage and promote long-term soil fertility.

## Effect of agroforestry on soil microbial carbon dynamics

Agroforestry systems significantly influenced soil microbial communities, which mediated carbon cycling and organic matter decomposition through enhanced root-microbe interactions. Root exudates from agroforestry trees contained simple sugars, amino acids and organic acids that served as an energy source for soil microbes, thereby stimulating microbial activity and enhancing soil carbon mineralization (74). Microbial biomass carbon (MBC) in agroforestry soils was reported to be 35–50 % higher than in conventional farming systems, directly contributing to SOC stabilization (74). Arbuscular mycorrhizal (AM) fungi further enhanced SOC sequestration by forming stable soil aggregates that protect carbon from microbial degradation and improved nutrient cycling efficiency (41). In silvopastoral systems, mycorrhizal colonization rates range from 65-75 %, significantly higher than the 30-40% observed I open pasture, highlighting their vital role in belowground carbon storage and soil fertility enhancement (57).

Agroforestry systems were found to store up to 300 Mg C ha$^{-1}$ in soil to 1 meter depth, with a sequestration rates ranging from 0.25-76.55 Mg C ha$^{-1}$yr$^{-1}$, making a substantial contribution to climate change mitigation (49, 54). Additionally, agroforestry practices increase soil nutrient availability by 20-50 % compared to conventional agriculture, promoting a shift towards fungal-dominated microbial communities that enhanced SOC accumulation (75). Improvements in the physical, chemical and biological properties of soil under agroforestry systems resulted in a 40-60 % reduction in erosion, a 25-40 % increase in biodiversity and greater crop productivity under water stress conditions (20). Despite these benefits, further research was needed to refine SOC stabilization mechanisms and accurately quantify long-term SOC storage potential of agroforestry systems, under varying soil types, tree species and climate conditions (54).

## Agroforestry's role in greenhouse gas (GHG) mitigation

Agroforestry was recognized highly effective climate change mitigation strategy, reducing greenhouse gas (GHG) emissions, particularly nitrous oxide ($N_2O$), methane ($CH_4$) and carbon dioxide ($CO_2$), while simultaneously enhancing carbon sequestration. Unlike monoculture systems, which contribute to high GHG emissions due to excessive fertilizer use and soil degradation, agroforestry improved nutrient cycling, promotes methane oxidation and regulated soil respiration regulation. Nitrogen-fixing trees such as *Leucaena leucocephala* and *Albizia lebbeck* contributed 100-250 kg N $ha^{-1}yr^{-1}$ through biological nitrogen fixation, significantly reducing reliance on synthetic fertilizers and lowering $N_2O$ emissions by 20-50 % (33, 34). Agroforestry systems reduced soil disturbance, leading to 30-50 % decrease microbial-mediated nitrous oxide emissions compared to conventionally tilled monocultures (76).

Additionally, agroforestry mitigates methane emissions by improving soil aeration and accelerating organic matter decomposition, thereby suppressing methanogenic bacterial activity in waterlogged soils (77). In degraded or deforested area, the establishment of agroforestry systems lowered overall GHG emissions by up to 30 % compared to conventional farming (54). Beyond emissions reduction, agroforestry sequesters carbon, with systems storing between 30 and 300 Mg C $ha^{-1}$ at depths of up to 1 m, significantly outperforming monoculture croplands (54, 57). The integration of trees and perennial crops further enhanced SOC sequestration by improving aggregation and minimizing carbon losses through oxidation (57). Agroforestry also delivered multiple co-benefits, including improved food security, increased farm income, biodiversity conservation and enhanced soil health, making it a key strategy for climate adaptation and resilience (78).

However, despite its potential, agroforestry remained underrepresented in agricultural GHG mitigation programs, particularly in the United State. This emphasized the need for further research into carbon accounting methods, supportive policy frameworks and boarder awareness of its environmental and socio-economic benefits (78). Integrating agroforestry into national and global climate strategies, could position it as a cornerstone for achieving carbon neutrality and sustainable land management.

## Reduction of nitrous oxide ($N_2O$) emissions through enhanced nitrogen use efficiency

Agroforestry systems significantly influenced nitrogen (N) dynamics and nitrous oxide ($N_2O$) emissions, offering potential for both mitigation and optimization of nitrogen use in agricultural landscapes. These systems generally reduced nitrogen losses through erosion, runoff and leaching compared to monocultures, with studies indicating a 30–70 % reduction in total N losses due to tree-root interactions and enhanced nutrient retention (79, 80). However, $N_2O$ emissions within agroforestry systems varied, depending on management practices, tree species and soil conditions. For instance, the incorporation of improved-fallow legume residues was shown to increase $N_2O$ emissions compared to natural-fallow residues, with emissions positively correlating to residue N content, sometimes exceeding those from monoculture systems (81). Conversely, the inclusion of nitrogen-fixing trees such as *Gliricidia sepium*, *Acacia spp.* and *Faidherbia albida* contributed to biological nitrogen fixation (BNF) (82), reducing synthetic fertilizer requirements by up to 30–50 % and subsequently lowering $N_2O$ emissions associated with fertilization (13). Maize intercropped with *Faidherbia albida* was reported to reduce $N_2O$ emissions by 40 % compared to maize monocultures (67).

Additionally, agroforestry enhanced SOM and microbial diversity, optimizing the nitrification-denitrification balance and preventing excessive $N_2O$ release (74). The presence of deep-rooted trees further improved nitrogen cycling by promoting N uptake from deeper soil layers, reducing the potential for nitrate leaching (83). The use of enhanced efficiency fertilizers (EEFs) in agroforestry systems also offered promise for mitigating $N_2O$ emissions by improving nitrogen use efficiency (NUE), though their effectiveness depended on factors such as soil moisture, temperature and microbial activity (84). Given that agricultural $N_2O$ emissions were projected to increase by 24-31 % by 2050 due to rising nitrogen inputs and effects of climate change (85).Strategies such as agroforestry, improved NUE and BNF-based fertilization played a critical role in mitigating these emissions while maintaining productivity (86). With $N_2O$ having a global warming potential (GWP) 298 times greater than $CO_2$ over a 100-year period, integrating agroforestry into agricultural systems presented a viable solution for reducing emissions, improving soil fertility and enhancing climate resilience (8).

## Methane ($CH_4$) oxidation potential in agroforestry systems

Methane ($CH_4$) was a potent greenhouse gas with a global warming potential (GWP) 25 times higher than carbon dioxide ($CO_2$) over a 100-year period (8). Unlike rice paddies and intensive livestock systems, which contributed significantly to $CH_4$ emissions, agroforestry served as a methane sink by enhancing methanotrophic microbial activity in soils. Methanotrophic bacteria oxidized $CH_4$ in aerobic soils, converting it into $CO_2$ and water, thereby reducing its release into the atmosphere. Studies showed that agricultural soils, including those under agroforestry, exhibited high $CH_4$ oxidation potential, particularly when exposed to elevated $CH_4$ concentrations (87). For example, tropical agroforestry soils demonstrated $CH_4$ uptake rates ranging from 0.3 to 1.2 mg $CH_4$ $m^{-2}$ $d^{-1}$, contributing to methane mitigation in both wet and dry seasons (88). Furthermore, tree-based intercropping systems enhanced $CH_4$ oxidation compared to conventional monocropping, with up to 40 % higher oxidation rates observed in intercropped soils (89).

Silvopastoral agroforestry systems, which integrated trees with pasture and livestock, showed methane emissions reductions of 30-50 % associated to conventional open grazing systems due to improved forage quality and greater microbial activity in soils (57). The occurrence of deep-rooted trees in agroforestry enhanced soil aeration, creating conditions favourable for methanotrophic bacteria to thrive. Research indicated that methane oxidation rates in agroforestry systems reached 1.5-2.0 kg $CH_4$ ha[-1] yr[-1], compared to just 0.5-0.8 kg $CH_4$ ha[-1] yr[-1]in conventional monocultures (90). Additionally, the integration of leguminous fodder trees, such as *Calliandra calothyrsus*, into livestock-based agroforestry was found to reduce enteric fermentation in ruminants (91), lowering $CH_4$ emissions by 15-25 % due to improved protein intake and reduced fiber digestion time (40). However, nitrogen fertilization suppressed $CH_4$ oxidation in various ecosystems, including forests and agricultural lands, due to competition between ammonium ($NH_4$+)-oxidizing and methane-oxidizing bacteria, which reduced $CH_4$ oxidation rates by 20-60 % (92). Despite this challenge, agroforestry remained a promising strategy for $CH_4$ mitigation through enhanced soil microbial activity, improved forage management and optimized nitrogen application, making it an integral component of sustainable agricultural systems.

### Impact on soil respiration and $CO_2$ flux regulation

Agroforestry systems exhibited complex soil $CO_2$ efflux dynamics influenced by various biotic and abiotic factors, including temperature, soil moisture, microbial activity and vegetation type. Soil respiration rates typically peaked under intermediate soil moisture conditions and declined during dry periods due to water limitations on microbial and root respiration (93). Seasonal variations in rainfall significantly influenced $CO_2$ efflux, with higher emissions verified during rainy seasons due to increased microbial activity and root respiration (94). However, agroforestry systems validated resilience to drought conditions, displaying only minor reductions in soil $CO_2$ efflux associated to conventional monoculture systems, which experienced more pronounced declines under water stress (89). The decomposition of litter and root exudates contributed substantially to total $CO_2$ fluxes in agroforestry, with seasonal fluctuations reflecting variations in organic matter input and microbial decomposition rates (95). While total soil $CO_2$ emissions did not differ significantly between agroforestry and forest ecosystems, the rate of carbon processing and sequestration varied depending on soil type, microbial composition and vegetation structure (96).

Soil respiration was a chief constituent of the carbon cycle, regulating $CO_2$ flux between the soil and the atmosphere. While necessary for organic matter decomposition and nutrient cycling, excessive $CO_2$ release from soil degradation exacerbated global warming (58). Agroforestry helped regulate soil respiration rates by enhancing SOC fixation, microbial activity and root biomass turnover, ultimately contributing to climate change mitigation. Research indicated that agroforestry systems reduced $CO_2$ fluxes by 20-35 % related to conventional monoculture cropping systems, primarily due to increased carbon input from tree litter and root biomass, which stabilized soil carbon pools (34). Deep-rooted tree species, such as *Eucalyptus spp.* and *Azadirachta indica*, contributed to carbon stabilization by sequestering organic carbon in deeper soil layers, where it was less susceptible to microbial decomposition and atmospheric release (97). Additionally, the enhanced soil aggregation in agroforestry systems reduced erosion and physically protected SOC from oxidation and microbial breakdown, further promoting long-term carbon sequestration (98).

Arbuscular mycorrhizal (AM) fungi played a crucial role in enhancing soil carbon stability in agroforestry. These fungi formed symbiotic associations with tree roots, facilitating the transfer of carbon from plant biomass into stable organic forms within the soil (20). AM fungi reported to increased soil carbon storage by 25-40 %, contributing to a more stable carbon pool in agroforestry soils compared to conventional agriculture (99). Besides, the presence of trees in agricultural landscapes reduces temperature fluctuations and moderated soil microclimate conditions, further stabilizing microbial activity and minimizing $CO_2$ emissions.

Beyond carbon sequestration and emission reduction, agroforestry enhanced resilience to climate variability by improving soil water retention, reducing heat stress and increasing biodiversity. The presence of trees in agroecosystems improved microclimate parameter by reducing wind speed and evapotranspiration rates, thereby conserving soil moisture during drought periods. According to report agroforestry enhanced soil moisture retention by 12-40 %, reducing the negative impact of erratic rainfall patterns on crop yields (66). In addition to its environmental benefits, agroforestry provided economic stability to farmers through diversified income sources, including timber, fruits, nuts, fodder and non-timber forest products. In drought-prone regions of Africa, for example, agroforestry systems integrating *Acacia senegal* for gum arabic production enabled farmers to maintain their livelihoods during severe droughts, highlighting the socio-economic benefits of tree-based farming systems (100).

### Agroforestry models for sustainable soil and carbon management

Agroforestry presented multiple land-use models that optimize carbon sequestration, soil fertility and ecosystem resilience. By integrating trees with agricultural or pastoral systems, these models improved SOC, enhanced nutrient cycling and mitigate soil degradation (101). Several agroforestry systems, including silvopastoral, alley cropping and agroforestry on degraded/ saline soils, demonstrated long-term sustainability benefits by reducing carbon emissions and improving soil structure.

### Silvopastoral systems

Silvopastoral systems (SPS), which integrated trees, pasture and livestock, played a critical role in improving carbon sequestration and enhancing SOM (102). Compared to conventional livestock grazing systems, SPS sequestered 2–5 times more carbon per hectare due to the combined effects of perennial tree biomass accumulation, enhanced grassland productivity and the incorporation of livestock waste into the soil (22). These systems leveraged deep-rooted trees, leguminous species and rotational grazing to maximize carbon storage while improving soil structure and fertility.

Research indicated that well-managed SPS stored 25-50 Mg C ha[-1] in AGB and up to 200 Mg C ha[-1]in the soil over a 20 -30 year period, significantly outperforming conventional grazing systems in terms of long-term carbon sequestration (33). Deep-rooted tree species such as *Leucaena leucocephala* and *Prosopis juliflora* contributed to carbon stabilization by transferring atmospheric $CO_2$ into deeper soil layers, where it was less susceptible to microbial decomposition and loss

(103, 104). Additionally, these trees enhanced biological nitrogen fixation (BNF), reduced dependency on synthetic nitrogen fertilizers and consequently lowered $N_2O$ emissions associated with intensive grazing lands (67).

SPS demonstrated superior carbon sequestration potential compared to both conventional pastures and monoculture forestry systems. Reports indicated that SPS sequestered 27-163 % more carbon than open pasturelands, which was attributed to increased SOC accumulation and greater biomass carbon inputs from trees and forage species (105). In arid northwestern India, SPS stored 36.3-60.0 % more SOC compared to tree-only systems and 27.1-70.8 % more than pasture-only systems, demonstrating their efficiency in optimizing carbon storage across different land-use types (106). Furthermore, studies in Argentina, Mexico and tropical American ecosystems highlighted that well-managed SPS not only improved carbon sequestration but also contributed to the restoration of degraded landscapes, enhancing ecosystem resilience and productivity (69, 107).

Beyond carbon sequestration, SPS provided multiple ecosystem services, including improved water retention, increased biodiversity and reduced land degradation. Tree canopy cover in SPS helped mitigate heat stress in livestock, leading to better weight gain and productivity compared to open grazing systems. Additionally, integrating fodder trees such as *Calliandra calothyrsus* and *Gliricidia sepium* into SPS improved forage quality and digestibility, reducing enteric methane ($CH_4$) emissions from ruminants by 15-25 % (40).

## Impact oquality and livestock productivityn soil

Silvopastoral systems improved soil fertility by enhancing nutrient cycling through leaf litter decomposition, root turnover and incorporation of animal manure. The presence of multipurpose trees in grazing lands increased soil nitrogen content by 30-50 % related to open pastures (40). Moreover, shade-providing trees reduced heat stress in livestock, resulting in higher milk yield and greater weight gain in cattle (14).

Soil microbial activity was significantly higher in silvopastoral systems, as the organic inputs from trees and livestock waste create an enriched rhizosphere. This promoted phosphorus solubilization, organic matter decomposition and microbially driven carbon sequestration, making the system biologically active and sustainable (74).

## Alley cropping and hedgerow systems: contribution to soil nutrient cycling and erosion control

Alley cropping, a sustainable agroforestry practice that integrates crops between hedgerows of trees or shrubs, has demonstrated significant potential for soil conservation, nutrient cycling and yield improvement in various agroecosystems. This system enhanced soil fertility by recycling nutrients through prunings, which served as mulch and organic manure, thereby reducing the need for synthetic fertilizers and improving crop productivity (108). Additionally, hedgerows planted along contours acted as natural barriers against soil erosion, particularly on sloping lands, where they substantially decreased soil loss compared to conventional tillage methods (109). Research indicated that alley cropping, when combined with mulching and minimum tillage, reduced soil erosion rates from 100-200 t $ha^{-1}$ $yr^{-1}$ under traditional farming to less than 5 t $ha^{-1}$ $yr^{-1}$, mainly by decreasing runoff volume and sediment transport (110). The incorporation of nitrogen-fixing trees such as *Gliricidia sepium* and *Sesbania sesban* between crop rows further enhanced nutrient cycling and soil fertility. These trees contributed to BNF, replenishing soil nitrogen levels and reducing reliance on synthetic fertilizers. Alley cropping was reported to increase soil nitrogen by 20-35 % compared to conventional monoculture systems, leading to sustained soil fertility and improved crop yields (65). Additionally, the periodic pruning of hedgerows provided a steady supply of organic matter, which fostered microbial activity and enhanced soil structure, improving aeration and water infiltration.

Beyond soil fertility, alley cropping played a crucial role in reducing soil erosion and conserving topsoil. In sloped landscapes, the extensive root systems of hedgerow trees anchored soil particles, reducing soil loss by 50-80 % and preventing gully formation - a major issue in erosion-prone areas (111). Moreover, the accumulation of leaf litter and organic matter enhanced soil moisture retention, mitigating drought stress and improving water-use efficiency. Alley cropping systems were shown to improve soil moisture availability by 12-35 %, offering a significant advantage in water-limited environments (66). In addition to soil and water conservation benefits, alley cropping provided additional economic and ecological advantages. The inclusion of multipurpose trees such as *Leucaena leucocephala*, *Calliandra calothyrsus* and *Acacia angustissima* not only supplied high-protein fodder for livestock and generated supplementary income through firewood, timber and biomass production (112). Farmers practicing alley cropping reported increased economic resilience, with diversified income sources reducing vulnerability to crop failures caused by climate variability (113).

Despite its numerous advantages, the widespread adoption of alley cropping faced challenges, including labour -intensive management, competition between trees and crops for nutrients and the necessity for farmer training on species selection and pruning techniques. Addressing these limitations through policy support, farmer incentives and participatory research could have enhanced the adoption of alley cropping as a scalable, climate-smart agricultural practice.

## Economic and ecological sustainability of alley cropping

Alley cropping significantly enhanced economic resilience by diversifying farm income through production of timber, fodder and fuelwood while simultaneously improving soil fertility and crop productivity. In Africa, alley cropping systems that incorporated *Leucaena spp.* and *Gliricidia spp.* have demonstrated maize yield increases of 50–70 %, mainly due to enhanced nitrogen availability and high organic matter input, which reduced dependence on synthetic fertilizers (67). This reduction in fertilizer costs directly improved farm profitability, making alley cropping an economically feasible alternative to conventional farming systems. Moreover, the integration of high-value tree species such as *Juglans nigra* (black walnut) and *Acacia angustissima* provided extra revenue streams through timber and specialty crops, further strengthening farm resilience (114).

Ecologically, alley cropping served as central strategy for conserving biodiversity and promoting ecosystem sustainability. The system supports a diverse range of pollinators and beneficial insects, reducing the reliance on chemical pesticides and promoting natural pest control. The increased vegetative cover and diversified habitat structure in alley cropping fields enhanced populations of predatory insects and pollinators, leading to improved crop health and yields (38, 39). Moreover, alley cropping contributed to greater soil biological activity, with microbial-driven carbon sequestration increasing by 25-40 % compared to monoculture systems, thereby improving soil carbon storage and mitigate the effects of climate change(115).

Beyond nutrient cycling and biodiversity enrichment, alley cropping also contributed to soil conservation by reducing erosion, increasing water infiltration and boosting soil structure. Alley cropping systems significantly enhanced soil aeration and protected against the erosive effects of rainfall, particularly when combined with mulching and conservation tillage (116). In Haiti, use of alley cropping with contour hedgerows effectively conserve topsoil, create enriched microsites for crop growth and provided essential resources such as fodder and fuelwood for smallholder farmers (117).

Likewise, research on alfalfa-black walnut alley cropping systems suggested that wider alley configurations-maintained crop yields comparable to those of monocropping while offering enhanced ecological benefits. These systems increased alfalfa weevil mortality rates by improving habitat conditions for natural predators, thereby demonstrating both agronomic and ecological viability (118).

Despite its many advantages, the long-term sustainability of alley cropping systems required continuous refinements in management practices. Systematic monitoring of tree-crop interactions, nutrient cycling efficiency and economic returns was essential to optimize planting densities, pruning plans and species selection. Additionally, addressing challenges such as tree-crop competition and labour-intensive management through farmer training and policy support proved crucial for promoting the broad adoption of alley cropping as a climate-resilient and economically sustainable agroforestry approach.

## Agroforestry for restoring degraded and saline soils: strategies for soil rehabilitation and sustainable land management

Agroforestry proven to be an effective strategy for rehabilitating salt-affected and degraded lands by improving soil properties, increasing productivity and providing critical ecosystem services. The integration of salt-tolerant tree species such as *Prosopis juliflora*, *Acacia nilotica* and *Casuarina equisetifolia* into agroforestry systems reduced soil pH, electrical conductivity and exchangeable sodium percentage, while improving water infiltration, soil fertility and cation exchange capacity (119). Specific techniques, such as the ridge-trench system, further enhanced soil restoration by facilitating root penetration and nutrient cycling in alkali soils (120). The presence of deep-rooted trees contributed to lowering the water table and preventing salt accumulation in the root zone (121). Earlier reports indicated a 30-50 % reduction in soil salinity over a 5-10 year period in agroforestry-based reclamation systems (122).

Beyond soil improvement, agroforestry enhanced the restoration of degraded lands by increasing SOC, improving microbial activity and strengthening soil structure. Intensive monoculture farming and deforestation had led to soil erosion, nutrient depletion and a decline in microbial diversity, but agroforestry helped reverse these effects by stabilizing soils and promoting organic matter accumulation. Research suggested that agroforestry-based land restoration could sequestered 2.5-4.0 Mg C $ha^{-1}$ $year^{-1}$, significantly increasing carbon stocks compared to non-vegetated degraded lands (39). In addition, silvopastoral systems that integrated saline-tolerant forages and trees improved livestock productivity while enriching soil conditions, making agroforestry a viable solution for restoring degraded grazing lands (121, 123).

Agroforestry also contributed to economic and ecological sustainability by diversifying farm income and increasing resilience to climate change. The integration of multipurpose trees provided several revenue streams through timber, fuelwood, fodder and non-timber forest products, offering long-term economic benefits to farmers in salt-affected regions. Moreover, agroforestry played a central role in carbon sequestration, biodiversity conservation and climate adaptation by enhancing soil resilience to extreme weather events and improving nutrient cycling through microbial activity (124). By executing tree-based restoration strategies and optimizing tree-crop-livestock interactions, agroforestry demonstrated strong proved to be a powerful approach for transforming degraded and saline landscapes into productive, climate-resilient ecosystems.

### Use of halophytic and drought-resistant tree species

Drought-resistant and salt-tolerant tree species were vital for afforestation in arid and saline regions, providing both ecological and socioeconomic assistances. The effective selection of tree species required assessing their drought resistance using methods such as the Drought Resistance Index (DRI), which evaluated leaf water potential as an

**Table 3.** Salt affected soils - amelioration through agroforestry in India

| Place | Tree species adapted | Soil depth (cm) | Original | | After | | References |
|---|---|---|---|---|---|---|---|
| | | | pH | EC ($dSm^{-1}$) | pH | EC ($dS\ m^{-1}$) | |
| Karnataka | *Acacia nilotica* (age 10 years) | 0–15 | 9.2 | 3.73 | 7.9 | 2.05 | (136) |
| Karnal | *Eucalyptus tereticornias (age 9 years)* | 0–10 | 10.06 | 1.90 | 8.02 | 0.63 | (137) |
| Lucknow and Bahraich | *Terminalia arjuna* | 0–15 | 9.60 ± 0.42 | 1.47 ± 0.45 | 8.40 ± 0.27 | 0.31 ± 0.07 | (138) |
| | *Prosopis juliflora* | 0–15 | 9.60 ± 0.42 | 1.47 ± 0.45 | 8.70 ± 0.33 | 0.42 ± 0.06 | |
| | *Tectonagrandis* | 0–15 | 9.60 ± 0.42 | 1.47 ± 0.45 | 6.15 ± 0.23 | 0.06 ± 0.006 | |

indicator of plant resilience (125). In India, tolerant tree species were used to ameliorate saline soils as presented in Table 3. Salt tolerance in trees was governed by a combination of genetic, physiological and anatomical adaptations, including enhanced root exudation, ion compartmentalization, leaf succulence and wood structure modifications that minimize water loss (126). A systematic framework for dryland afforestation prioritized species that enhanced ecosystem functions while supporting local livelihoods, balancing native and non-native species selection based on ecological suitability and socioeconomic value (127). The incorporation of stakeholder participation and experimental testing of candidate species ensured long-term afforestation success while minimizing ecosystem disruption.

For afforestation on saline and degraded soils, the selection of salt-tolerant and drought-resistant species was critical for enhancing soil fertility and resilience. Species such as *Acacia nilotica*, *Prosopis juliflora*, *Atriplex* spp. and *Casuarina* spp. demonstrated superior adaptability to high-salinity environments, with deep-rooted systems that facilitated salt leaching and improved soil aeration. These species contributed to carbon sequestration by increasing SOC through litter deposition and root turnover. Investigation indicated that integrating salt-tolerant species into agroforestry systems enhanced microbial-driven carbon sequestration and nutrient cycling, reducing the dependency on chemical soil amendments (123). Furthermore, tree-based systems improved soil structure by increasing aggregation and stabilizing soil particles, thereby reducing erosion and preventing further degradation in fragile landscapes.

Halophytic tree species served a central role in improving rhizosphere microbial diversity, which aided in nutrient solubilization, organic matter decomposition and salt leaching. Planting halophytes in saline soils increased microbial biomass by 30 % and reduced soil electrical conductivity by 40 % over a five-year period (108). In addition, agroforestry systems established in degraded were shown to improve soil water-holding capacity by 20-35 %, mitigating the impacts of drought and reducing the risk of desertification (128). These findings highlighted the potential of tree-based afforestation strategies to rehabilitate degraded lands while enhancing agricultural sustainability. By integrating salt-tolerant and drought-resistant species into afforestation initiatives, agroforestry served as a climate-resilient solution to land degradation and desertification challenges.

## Socioeconomic and cultural benefits of agroforestry

Agroforestry enhanced socioeconomic resilience by diversifying income sources, improving farm productivity and strengthening rural livelihoods. Contrary to conventional agriculture, agroforestry integrated trees, shrubs and livestock, reducing financial risks and increasing sustainability. Investigation indicated that agroforestry can boosted farm income by 20-50 %, depending on species selection and management practices (129). Farmers benefited from multiple revenue streams through the sale of timber, fuelwood, fodder, fruits and medicinal plants, although tree-based systems enhance soil fertility and moisture retention, leading to 15-30 % higher crop yields associated to monocultures (130). Fuelwood and fodder production were vital in resource-scarce regions, with fast-growing species like *Leucaena leucocephala*, *Gliricidia sepium* and *Prosopis juliflora* meeting 50-80 % of household fuelwood desires in sub-Saharan Africa, reducing pressure on natural forests (65). Moreover, agroforestry-based fodder systems improved livestock productivity, increasing milk yields by 25-40 % when protein-rich fodder trees such as *Calliandra calothyrsus* and *Sesbania sesban* are integrated (131, 132).

In addition to economic advantages, agroforestry contributed to preservation of cultural heritage, the promotion of ecotourism and the advancement of community development. Traditional agroforestry systems, such as home gardens in South and Southeast Asia, functioned as a reservoir of indigenous knowledge and served as important centre of biodiversity hotspots. Ecotourism-linked agroforestry farms generated 10-30 % more income than monoculture farms by attracting visitors interested in agroecological farming practices and nature based tourism (133). Agroforestry also fostered social cohesion through community-based activities such as collective tree planting, watershed management and carbon credit initiatives, strengthening community ties and promoting environmental stewardship. Notably, women-led agroforestry programs in Africa and South Asia contributed to 15-40 % higher household incomes through involvement in nursery management and the harvesting of non-timber forest product, advancing gender equity and enhancing economic autonomy (66). These diverse benefits underscore agroforestry's role in promoting sustainable rural development and enhancing climate resilience.

## Challenges and opportunities in agroforestry for soil and carbon management

Agroforestry presents a promising solution for improving soil health and sequestering carbon. But its extensive adoption was hindered by economic, policy and technological barriers. A key challenges was the long-term investment required as agroforestry systems, which take several years to generate financial returns unlike annual cropping. This discouraged farmers from adopting such practices particularly smallholder farmers in developing countries who faces high initial costs and uncertain short-term profitability (66). Policy-related barriers, including inconsistent regulations on tree planting, harvesting and land-use classification, further restricted the expansion of agroforestry. Governments must introduce financial incentives, such as carbon credits and tax benefits - to encourage farmers to integrate trees into their farming systems. Research showed that well-managed agroforestry projects can generate $ 30-$ 100 per hectare annually through carbon credit programs (34) highlighting the economic potential of these systems.

Another major barrier to agroforestry adoption was insecure land tenure. In many regions, land ownership laws did not grant smallholder farmers the legal rights necessary to invest in long-term agroforestry projects. A study in sub-Saharan Africa found that over 50 % of rural land remained informally owned, making farmers hesitant to establish tree-based systems requiring decades of management (134). Conversely, countries with strong land tenure policies, such as Costa Rica, experienced a 35 % increase in agroforestry adoption due to government- supported carbon payment programs (102). Implementing land tenure reforms and integrating agroforestry into national climate action plans can significantly boosted adoption rates. Financial mechanisms including low-interest loans, subsidies and direct payments for ecosystem services were prioritized to support farmers in transitioning to agroforestry-based land management.

Technological advancements also transformed agroforestry, making it a more viable strategy for soil carbon sequestration and climate resilience. Traditional carbon monitoring techniques, which relied on labour-intensive soil sampling, were replaced by remote sensing, LiDAR and artificial intelligence (AI)-driven modelling. Research demonstrated that remote sensing and LiDAR technology could estimate aboveground carbon stocks with over 90 % accuracy, providing a more efficient method of quantifying carbon sequestration potential (135). Precision agroforestry, employing IoT sensors and GIS-based mapping, enables real-time optimization of tree-crop-livestock interactions, thereby enhancing both carbon sequestration and soil fertility. In Kenya, IoT-based agroforestry management increased tree growth rates by 20 % and soil carbon accumulation by 15 % compared to traditional systems (17). Blockchain technology emerged as a transparent and secure process for trading carbon credits, allowing farmers to monetize their contributions to climate change mitigation. Future research was recommended to focus on developing cost-effective carbon monitoring tools, integrating AI-driven climate models and scaling up agroforestry innovations for global agricultural sustainability.

Despite existing challenges, agroforestry had the potential to transform soil health management and carbon sequestration. Addressing economic constraints through financial incentives, securing land tenure rights and leveraging technological advancements were essential for unlocking the full benefits of agroforestry. As global efforts to combat climate change intensified, policy frameworks increasingly prioritize agroforestry as a strategic approach for reducing greenhouse gas emissions, enhancing soil fertility and promoting sustainable farming systems. By overcoming adoption barriers and investing in research and development, agroforestry emerged as a cornerstone of climate-smart agriculture, offering long-term ecological and economic benefits for farmers and the environment.

## Conclusion and future prospects

Agroforestry stood as a nature-based solution for enhancing soil health, improving carbon sequestration and fostering climate-resilient agriculture. By integrating trees, crops and livestock, agroforestry systems contributed to SOC accumulation, nutrient cycling, microbial diversity and water retention. With a carbon sequestration potential ranging from 0.29 to 15.2 Mg C $ha^{-1}$ $year^{-1}$, agroforestry played a significant role in mitigating climate change while enhancing soil fertility and ecosystem services. Additionally, it reduced soil erosion, supported biodiversity and improves agricultural sustainability. Extensive adoption remained hindered due to economic constraints, policy barriers and insecure land tenure. Addressing these challenges required robust policy frameworks, financial incentives and research-driven innovations in carbon monitoring and precision agroforestry.

Looking forward, advancements in agroforestry research- including improved soil management practices, the selection of high-yielding and climate resilient tree species and the adaptation of digital technologies such as AI-based monitoring and blockchain enabled carbon trading, offered promising pathways for scaling adoption. International organizations and climate policies increasingly recognizing agroforestry's role in achieving sustainability goals. With targeted investments, supporting policies and farmer-centered extension programs, agroforestry had the potential to become a mainstream agricultural strategy, strengthening both environmental and economic resilience in the face of global climate challenges.

## Authors' contributions

KS is responsible for the collection of literature, structuring the manuscript, preparation and drafting the manuscript. GM contributed to the manuscript through overall guidance, development of the framework, correction and revision of the manuscript. MT, KR, PS and HBR participated in correcting and revision process. All authors read and approved of the final version of manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors declare that they have no conflicts of interest.

**Ethical issues:** None

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